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Agriculture, Ecosystems and Environment 110 (2005) 149–165
Agriculture Ecosystems & Environment
www.elsevier.com/locate/agee

Exploring diversity in soil fertility management of smallholder farms in western Kenya
I. Heterogeneity at region and farm scale

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Received 26 May 2004; received in revised form 14 March 2005; accepted 6 April 2005
Available online 29 April 2005

Abstract

The processes of nutrient depletion and soil degradation that limit productivity of smallholder African farms are spatially heterogeneous. Causes of variability in soil fertility management at different scales of analysis are both biophysical and socio-economic. Such heterogeneity is categorised in this study, which quantifies its impact on nutrient flows and soil fertility status at region and farm scales, as a first step in identifying spatial and temporal niches for targeting of soil fertility management strategies and technologies. Transects for soil profile observation, participatory rural appraisal techniques and classical soil sampling and chemical analysis were sampled across 60 farms in three sub-locations (Emuhaia, Shinyalu, Aludeka), which together represent much of the variability found in the highlands of western Kenya. Five representative farm types were identified using socio-economic information and considering production activities, household objectives and the main constraints faced by farmers. Soil fertility management and nutrient resource flows were studied for each farm type and related to differences in soil fertility status at farm scale. Farm types 1 and 2 were the wealthiest; the former relied on off-farm income and farmed small pieces of land (0.6–1.1 ha) while the latter farmed relatively large land areas (1.6–3.8 ha) mainly with cash crops. The poorest farm type 5 also farmed small pieces of land (0.4–1.0 ha) but relied on low wages derived from working for wealthier farmers. Both farm types 1 and 5 relied on off-farm earnings and sold the least amounts of farm produce to the market, though the magnitude of their cash, labour and nutrient flows was contrasting. Farms of types 3 and 4 were intermediate in size and wealth, and represented different crop production strategies for self-consumption and the market. Average grain yields fluctuated around 1 t ha^{-1} $year^{-1}$ for all farm types and sub-locations. Grain production by farms of types 4 and 5 was much below annual family requirements, estimated at 170 kg $person^{-1}$ $year^{-1}$. Household wealth and production orientation affected the pattern of resource flow at farm scale. In the land-constrained farms of type 1, mineral fertilisers were often used more intensively (ca. 50 kg ha^{-1}), though with varying application rates (14–92 kg ha^{-1}). The use of animal manure in such small farms (e.g. 2.2 t $year^{-1}$) represented intensities of use of up to 8 t ha^{-1}, and a net accumulation of C and macronutrients

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0167-8809/$ – see front matter
doi:10.1016/j.agee.2005.04.001

brought into the farm by livestock. In farms of type 5, intensities of use of mineral and organic fertilisers ranged between 0–12 kg ha^{-1} and 0–0.5 t ha^{-1}, respectively. A consistent trend of decreasing input use from farm types 1–5 was generally observed, but nutrient resources and land management practices (e.g. fallow) differed enormously between sub-locations. Inputs of nutrients were almost nil in Aludeka farms. Both inherent soil properties and management explained the variability found in soil fertility status. Texture explained the variation observed in soil C and related total N between sub-locations, whereas P availability varied mainly between farm types as affected by input use.

Keywords: Soil fertility gradients; Farm typology; Sub-Saharan Africa; Nutrient balances; Manure; Fertiliser

1. Introduction

Poor soil fertility is widely accepted as a major factor limiting productivity of smallholder farms in Africa (Sanchez et al., 1997). The processes of nutrient depletion and soil degradation, however, are spatially heterogeneous, as determined by the underlying parent material and geomorphology and by (current and historical) management (Smaling et al., 1997). Causes of variability in soil fertility management at different scales of analysis (i.e. region, village, farm, field) are both biophysical and socio-economic. Variability at regional scale is determined by climate and dominant soil types, presence of and access to factor and product markets and historical, socio-cultural and ethnic aspects defining land use. The variability between different farm types within a village is associated within the 'soilscape', such as the location along catenary sequences (Deckers, 2002) and with differences in soil fertility management between poor and wealthy households (Crowley and Carter, 2000). Resource availability and the pattern of resource allocation to different activities are determined by household 'wealth', and depend on household priorities and production strategies. Therefore, the intensity of the processes, potentially leading to variation in soil fertility status at the farm level and their dynamics will vary between farms of different resource endowment and production orientation.

The highlands of western Kenya support one of the densest rural populations in the world, as a result of large initial settlements attracted by the good soils in the area that were originally fertile. Population growth has led to gradual depletion of nutrients through crop-harvest removal, leaching, and soil erosion, which farmers have been unable to compensate via crop residues, manure and mineral fertilisers (Shepherd and Soule, 1998). Western Kenya is broadly representative of the situation found in other areas of the African highlands (Uganda, Ethiopia and Madagascar), with comparable soil types, climate, technology and demography (Braun et al., 1997). Rainfall in western Kenya ranges from 1400 to 2000 mm annually, decreasing westwards, and distributed in two cropping seasons: the long rains from March to July and the short rains from August to November. The landscape is gently undulating in the East to fairly flat in the West, with the exception of scattered groups of hills. Nitisols, Ferralsols and Acrisols are the predominant soil types (Jaetzold and Schmidt, 1982; Andriesse and Van der Pouw, 1985). Nitrogen and phosphorus are the main limiting nutrients in food crop production (Shepherd et al., 1997), although potassium deficiencies are locally important. Due to high population in the subsistence smallholder sector, average farm sizes tend to be small – from 0.6 ha (Vihiga district) to 2.2 ha (Teso district); population density in these rural areas ranges from 400 to 1300 inhabitants km^{-2} (Kenya Ministry of Agriculture and Rural Development, 2001). The land use systems are diversified and range from subsistence smallholdings in Siaya, Kakamega and Vihiga districts to more cash-crop oriented farms in the sugar belt and in the northern areas (Rotich et al., 1999).

Here, we describe research that was undertaken to understand the processes leading to the establishment of heterogeneity in soil fertility in smallholder farms of western Kenya. This was seen as a necessary step in identifying spatial-temporal niches for targeting of soil fertility management strategies and technologies. The objectives were (i) to identify and categorise the various biophysical (e.g. variation in soil types) and socio-economic (e.g. population density) factors affecting the soil fertility status at region and farm scale, (ii) to determine the magnitude of the nutrient

flows at farm scale, (iii) to construct farm typologies that reflect potential access of households to resources for managing their soils, equivalent to the ‘wealth class’ approach, and (iv) to develop a framework for categorising heterogeneity in soil fertility at different scales.

2. Materials and methods

2.1. Site selection

After a preliminary survey using agroecological (including soil) maps and field tours, three sub-locations (essentially groups of villages) were selected for detailed study in western Kenya: Emuhaia division in Vihiga district (0°4′N; 34°38′E), Shinyalu division in Kakamega district (0°12′N; 34°48′E) and Aludeka division in Teso district (0°35′N; 34°19′E). They encompassed much of the variability within western Kenya, in agreement with previous characterisation work in the region (e.g. Jaetzold and Schmidt, 1982; Crowley and Carter, 2000). Clear gradients in altitude, rainfall, topography and soil types as well as differences in population density, ethnic groups, access to markets and land use were observed between these sub-locations (Table 1), which represents the variability found in the

Table 1
Main biophysical characteristics, socio-economic indicators and main production activities of the selected working sites (Kenya Ministry of Agriculture and Rural Development, 2001; Crowley and Carter, 2000; Braun et al., 1997; FURP, 1994; Jaetzold and Schmidt, 1982)

Variable	Unit	Sub-location		
		Emuhaia	Shinyalu	Aludeka
Biophysical characteristics				
Altitude	m	1640	1820	1180
Annual mean temperature	°C	20.4	20.8	22.2
Total annual rainfall[a]	mm	1850	2145	1463
Long rains (66% probability)	mm	800	1094	830
Short rains (66% probability)	mm	660	727	540
Rain distribution				
Long rains		Begin. March to mid July	March to mid July	Begin. February to mid July
Short rains		End July to begin. December	July to begin. December	End July to end December
Topography		Moderately undulating (slopes 2–15%)	Very undulating (slopes up to 45%)	Gently undulating (slopes 2–5%)
Dominant soil type (local name/FAO)		Ingusi: nito-humic Ferralsol and dystro-mollic Nitosol	Ingusi: humic Nitosols and dystro-mollic Nitosols	Apokor: ferralo-orthic Acrisol, petroferric phase[b]
Socio-economic indicators				
Average farm size	ha	0.69	1.25	2.13
Population density[c]	Inhabitants km^{-2}	930	650	310
Family size		7.2	6.8	8.0
Ethnic group[d]		Luhya (Munyore)	Luhya (Isokha)	Teso
Production activities				
Food crops		Maize/beans	Maize/beans	Maize, cassava, finger millet
Cash crops		Tea, Napier grass, fruits and vegetables	Tea, coffee, sugarcane, fruits and vegetables	Cotton, tobacco, rice and finger millet
Livestock and grazing		Local zebu breeds but increasingly graded dairy cows; zero grazing units or tethered in the farm	Local zebu breeds and some graded dairy cows; zero grazing, tethered in farm or communal land	Local zebu breeds (oxen); free ranging on natural fallow land; affected by endemic Tripanosomiasis

[a] Average over 26, 14 and 21 years, respectively.
[b] With adjustments according to the Kenya concept (1980).
[c] In certain areas of Vihiga district (i.e. Maragoli, bordering Emuhaia to the North) population density can be as high as 1500 inhabitants km^{-2}.
[d] Tribe (sub-tribe).

region. Emuhaia and Shinyalu were closer to urban centres than Aludeka; the former was also located in the most densely populated district in western Kenya. Clearly, the groups of factors presented in Table 1 are not totally independent; e.g. population density results from the complex interaction of potential productivity (determined largely by rainfall and soil characteristics) and the socio-economic environment (e.g. access to factor markets, ethnical differences). An additional criterion to select these sites was practical: several projects have been conducted in the past in different villages within these three localities, yielding much background information used in this work.

The dominating ethnic group in western Kenya is the *Luhya*, comprised by several sub-tribes with differences in language and culture, but with a common agricultural background. The *Luo* people are found along the shores of Lake Victoria, considered earlier as fishermen, and on the border with Uganda live the *Teso* people, who are more broadly represented in that country than in Kenya. The major food crops grown by the smallholder sector are maize (*Zea mays* L.) and beans (*Phaseolus vulgaris* L.), followed by cassava (*Manihot esculenta* Crantz), sorghum (*Sorghum* spp.) and finger millet (*Eleusine coracana* L.). Main cash crops include tea (*Camellia sinensis* O. Kuntze), sugar cane (*Saccharum officinarum* L.), and secondarily cotton (*Gossypium hirsutum* L.) and tobacco (*Nicotiana tabacum* L.) in Teso district. Most cattle kept in the region are local Zebu breeds, but there is an increasing number of improved (Friesian) cows for dairy production near the urban centres. Due to the larger farm sizes and more availability of livestock, ploughing with oxen is more common towards the west.

2.2. Site biophysical characterisation

The distribution of major soil types across the landscape was studied within and between localities. Pits (1.2 m deep) were dug at different points along a topographic section and soil morphological attributes were described following the criteria of FAO as described by De Pauw (1985), and compared with previous profile descriptions (e.g. FURP, 1994). Local farmers' soil classification derived from interviews (see Section 2.3) was matched with the previously identified soilscape units (TSBF, 2001).

2.3. Farm selection and characterisation

Key informants (extension officers or knowledgeable farmers) assisted in developing an initial list of farmers who were 'good' and 'poor' soil fertility managers (about 30 per site, 90 in total; Tittonell, 2003). Information on number and distribution of production units, components of the farm system, farm assets and infrastructure, management practices, labour supply and family composition was gathered at 20 farms per sub-location (60 in total) by means of a semi-structured questionnaire and by drawing farm transects together with the farmers. Their answers were triangulated by asking the same questions in several ways or during different visits to the farms, by confirming with other family members, other farmers and with extension officers. In farms headed by men, women were also interviewed and the information cross-checked, as women were involved in most activities regarding crop and soil management.

2.4. Farm typology

An initial approach to classify farms based solely on resource endowment led to poor discrimination of resource allocation patterns. Adding information on production goals (e.g. self-subsistence, market orientation), the main types of constraints faced, position in the farm developmental cycle (Crowley, 1997) and main source of income improved the discrimination of farm typologies enormously. Graphic models of the farm system were made using this combined information gathered during initial interviews for all farms visited. The relative importance of each system component (Table 2), system boundary (i.e. Farm size) and the arrows representing the different flows was graphically represented by its size. Relationships between internal and external system components were defined in terms of cash (Kenya Shillings, KSh; US$ 1 = 75 KSh in 2002), labour (man-days) and nutrients (kg) flows. Estimates of nutrient flows included both fertiliser and biomass flows.

2.5. Resource flows at farm scale

Nutrient inputs and outputs at farm scale were calculated by estimating food production and marketing, and fertiliser use for one case study farm for each

Table 2
System components defined for the farm typology and their description

System component	Acronym	Description	Example
Food crops consumed by household	CSN	Crops grown on the farm to cover the food demands by the household	Maize, beans, sweet potato, local vegetables
Food crops sold on the market	MKT	Food crops grown in excess of the household food demands that are commercialised, requiring low inputs and/or low investments	Maize, beans[a], cabbage, groundnuts
Cash crops	CSH	Crops exclusively or predominantly grown for commercialisation that in most cases are not consumed by the household, requiring inputs and relatively high investments	Tea, coffee, sugarcane, cotton, certain vegetables
Livestock	LVSTK	Animal production activities demanding land and labour (sometimes inputs), generating cash or acting as investments	Dairy cows, goats, sheep, pigs
Woodlot	WOOD	On-farm source of fuel and/or construction wood, sometimes sold on the market	Eucalyptus and Grevillea woodlots
Other enterprises	OE	Other economical activities demanding labour (sometimes also land) and generating cash	Oxen services, honey bees
External food source	FOOD	Food items consumed by the household that are purchased on the market[b]	Maize, beans
External income source	OFF-FARM	Salary, pension, earnings from casual employment, submissions, rents and gifts flowing into the household	
Household	HOME	Family members living (and eating) on the farm, and members living outside and receiving remittances	

[a] Apparently overlapping with the previous category. The sum CSN + MKT indicates the totality of food crops produced on-farm, and CSN is the amount effectively consumed by the household.
[b] Except for those items that are always purchased, such as sugar, oil, etc.

of the farm types identified in each of the sub-locations (totalling 15 farms). Estimations were derived from the amounts harvested from and/or applied to the different fields as indicated by farmers, for the long rains season of 2002. Most quantities given by farmers were in local units, such as *goro-goros* (±2 kg of maize), *debes* (±8 kg of maize) or bags (80–90 kg of maize), and they were converted into SI units (Tittonell, 2003). Gross food production (GFP) was estimated by summing the fresh weight (FW) of the outputs of all fields within the farm indicated by the farmers, irrespective of their type (grains, tuber and roots, fruits, leaves). Fertiliser use was calculated from the amounts in local units applied to each field. Total fertiliser use [kg] at farm scale was aggregated from the amount used in each field; it was divided by the total area under crops (fertilised or not) within a farm [ha] to obtain the fertiliser use intensity [kg ha^{-1}]. Fertiliser application rates [kg ha^{-1}] were calculated for each particular field; the average application rate was calculated considering only those fields where fertilisers were applied. The nutrient content of different materials, such as cattle manure, previously measured for a number of farms of different wealth classes in the region was obtained from literature (Rotich et al., 1999; Palm et al., 2001; TSBF, 2001), and used to estimate nutrient flows.

2.6. Soil sampling and laboratory analysis

Topsoil (0–15 cm) samples were taken with an auger at five points per field from all the production units identified in the 15 case-study farms. A composite sample of approximately 0.75 kg from each field was taken to the laboratory for soil analyses. Soil samples were air-dried, sieved through 2 mm, stored at room temperature, and were analysed, following standard methods widely used for tropical

soils (Anderson and Ingram, 1993). Soil pH was determined in water using a 1:2.5 soil/solution ratio. Samples were extracted with 1 M KCl using a 1:10 soil/solution ratio, analysed by NaOH titration for exchangeable acidity and by atomic absorption spectrometry for exchangeable Ca and Mg. Samples with pH >5.5 were assumed to have zero exchangeable acidity and samples with pH <7.5, zero exchangeable Na (all samples in this case). Samples were extracted with 0.5 M $NaHCO_3$ + 0.01 M EDTA (pH 8.5, modified Olsen) using a 1:10 soil/solution ratio and analysed by flame photometer for exchangeable K and colorimetrically (molybdenum blue) for extractable P. Organic C was determined colorimetrically after H_2SO_4 – dichromate oxidation at 150 °C for 30 min. Total N was determined by Kjeldhal digestion with sulphuric acid and selenium as a catalyst. Particle-size distribution was determined using the hydrometer method after pre-treatment with H_2O_2 to remove organic matter (Gee and Bauder, 1986). Effective cation-exchange capacity (ECEC) was calculated as the sum of exchangeable acidity and exchangeable bases.

Weighted average soil fertility indicators were obtained by affecting the results of the laboratory analysis of each individual field by the proportion of its area relative to total farm area, according to the following equation:

$$\mathrm{SFS}_{(\mathrm{X})} = \sum_{i=1}^{n} \mathrm{SF}_{(\mathrm{X})i,n} \times \frac{\mathrm{FA}_i}{\mathrm{TFA}}$$

where, $\mathrm{SFS}_{(X)}$ = soil fertility status at farm scale for nutrient X; $\mathrm{SF}_{(\mathrm{X})i,n}$ = soil fertility status (i.e. stock, availability) as determined by soil analysis for each field in the farm (1–n fields); $\mathrm{FA}_{i,n}$ = area of each particular field (1–n fields) [ha]; TFA = total farm area [ha]

2.7. Statistical analysis

The information derived from the semi-structured interviews was expressed as both average values for different socio-economic indicators (e.g. family size, number of cattle) and frequencies (%), indicating the degree of adoption and/or use of management practises and inputs. The statistical significance of the differences between farms of different strata for the various socio-economic indicators was assessed by analysis of variance using Genstat Release 6. The model considered the factors of sub-location, farm type and their interaction.

3. Results

3.1. General description of the farms in the different target areas

Farms selected for this study were concentrated within the main representative soil-landscape units, which were revealed by the transects for soil observation delineated at each particular sub-location (Fig. 1). In Emuhaia and Shinyalu, most farms were concentrated on the locally-termed *Ingusi* soils (Nitosols and Ferralsols) whereas in Aludeka, with a larger farm size and a more uneven soil distribution, farms were selected that had *Apokor* soils (ferralo-orthic Acrisols) on most of their land. Soil depth and texture were the main sources of biophysical variability within the farms of Aludeka, due to the relatively flat landscape. Larger farms belonging to the wealthier classes tended to include more than a single soil-landscape unit within their boundaries. Most farms in all sub-locations hired casual labour, but hiring of permanent labour was more often seen in Emuhaia (data not shown). Farmers from the poorer classes often derived income by working for other farmers during land preparation, planting, weeding and harvesting times. These and other off-farm opportunities were reflected by the smaller percentage of the total household income generated by farming in Emuhaia, where ca. 80% of the farmers interviewed earned part of their income outside their farm. The percentage of female household heads was higher in Emuhaia and Shinyalu (50 and 37%, respectively) than in Aludeka (11%), as well as the number of widows. The percentage of people with a secondary education level in Emuhaia was almost twice as high as in Shinyalu and Aludeka, probably due to the proximity and easier access to urban areas. Most farms in Emuhaia owned livestock (i.e. cattle, goats, sheep and pigs), which was less related to differences in wealth than for the other sub-locations. The epidemic disease *Tripanosomiasis* in Aludeka was the cause of a smaller proportion of farms owning cattle. In Emuhaia, due to the smaller farm sizes,

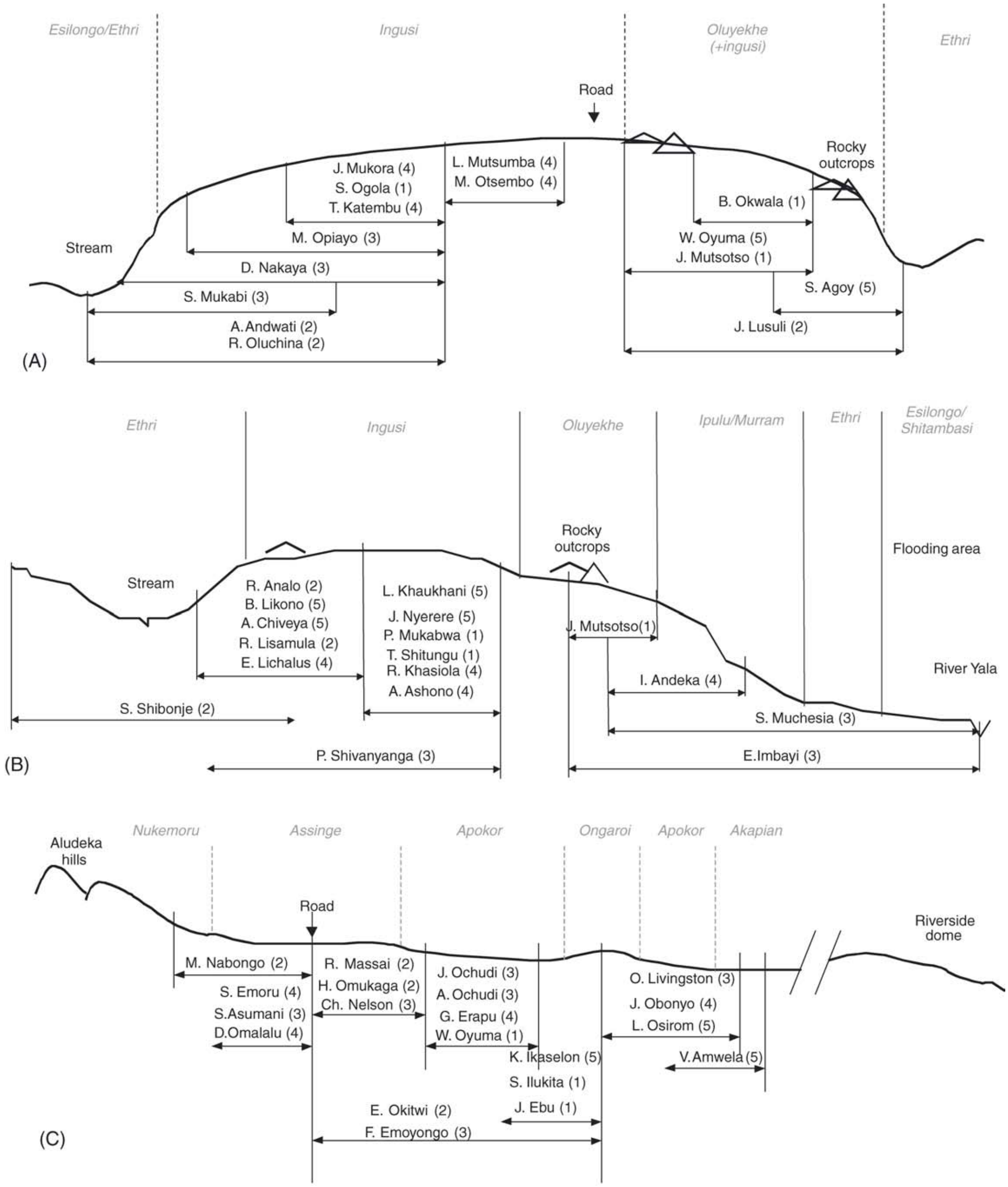

Fig. 1. Distribution along the landscape of the interviewed and sampled farms in Emuhaia (A), Shinyalu (B) and Aludeka (C), western Kenya. Names in *italics* indicate local terms for soil/landscape units identified by farmers. The names of the farmers (household head) are followed by the farm type to which they belong, into brackets. The arrows below the farmers' names indicate the soilscape units on which the sampled farms are placed (e.g. Mr. E. Okitwi's farm in Aludeka, which belongs to the type 2, includes *Assinge*, *Apokor* and *Ongaroi* soils within its area). (A and B) represent sections ranging between 2 and 5 km distance from valley to valley; in (C), the distance from the hills to the river ranges between 5 and 10 km.

40% of the households had no source of fuelwood on their land; they covered their fuel needs by purchasing wood and/or using crop residues. Self-sufficiency in maize production was achieved by less than 40% of farmers in all sub-locations.

In Emuhaia and Shinyalu the homestead was normally located in the uppermost part of the farm (cf. Fig. 1), near the roads that generally run along the top of the ridges in this heavily dissected landscape. The homestead was surrounded by living fences delimiting a compound often used as grazing place for tethered cattle with scattered trees for shade, fruits or wood. Bananas and (local) vegetables intercropped with pulses and grains were grown around the house. In large farms, the furthest fields from the homestead occupied the extreme slopes or the valley bottoms. In some farms of Shinyalu, the homestead was moved to a different place within the farm after about 10–15 years, to make use of the fertility accumulated around it by growing crops. In Aludeka the compounds were not used for grazing; the homestead was often placed in the centre of the land and surrounded by banana plants and fruit trees. Maize and groundnuts (easily stolen crops) tended to be grown nearer the house, while cassava and finger millet were mainly found in further fields. Many farms had remote fields with a permanent fallow of thatching grass (*Hyparrhenia* spp.) used for roofing. In the few farms with cattle, they were kept in a boma (stall) during the night. In all sub-locations, fodder crops like Napier grass and annual vegetables (e.g. kale, cabbage or tomatoes) were grown as cash crops in small areas of good quality land.

3.2. Farm typology and stratification

Five farm types were defined using the combination of wealth and production criteria (Table 3). Most farms in types 1 and 2 fell into the wealthiest class, farms of type 3 in the middle class and farms type 5 in the poorest class. Some farms of type 4 fell into the middle class, though most of them into the poor, with a different distribution across localities. The farm types were consistent across sub-locations (Fig. 2), though slight differences were often observed due to differences in the production system and socio-cultural characteristics. In all sub-locations, only the farm types 2 and 3 were self-sufficient in food production and obtained only some specific food items (e.g. oil, sugar, etc.) on the market.

In farms of type 1 the household head and/or another family member worked outside the farm earning a fixed salary, or had a shop or other sort of permanent off-farm income. Type 2 farms were typically large and wealthy with a large family, where labour was hired to replace that of children who were studying, and for labour-intensive activities (e.g. tea picking). In farms of type 3 most income was generated by farming, and they normally had surpluses of food crops for the market. Input-demanding activities such as perennial cash crops (e.g. tea) were not widely adopted due to financial

Table 3
Characteristics of the identified farm types according to the main five criteria considered for their categorisation

Farm type	Wealth class	Production orientation	Main constraints	Position in farm cycle, family structure	Main source of income
1	Mainly HRE, few MRE	Mainly self-consumption	Land, (labour)	Variable age of HH, small family	Salary, pension, etc.
2	HRE	Market-oriented	(labour)	Old HH, large family, start dividing land	Cash crops and other farm produce
3	MRE	Self-consumption and (low-input) market-oriented	Capital, sometimes labour	Young to mid-aged HH, variable family size (young), in expansion phase	Farm produce, surpluses, other enterprises
4	Mainly LRE, some MRE	Self-subsistence	Land and capital	Young to mid-aged HH, variable family size	Services, little farm produce
5	LRE	Self-subsistence	Land, capital and labour	Variable age of HH, variable family size, often women-headed farms	Selling labour

HH: household head; HRE, MRE and LRE: high, medium and low resource endowment (i.e. land size, livestock ownership, type of homestead, etc., Crowley, 1997), respectively; (labour) indicates that the initial limitation was removed by hiring in labour.

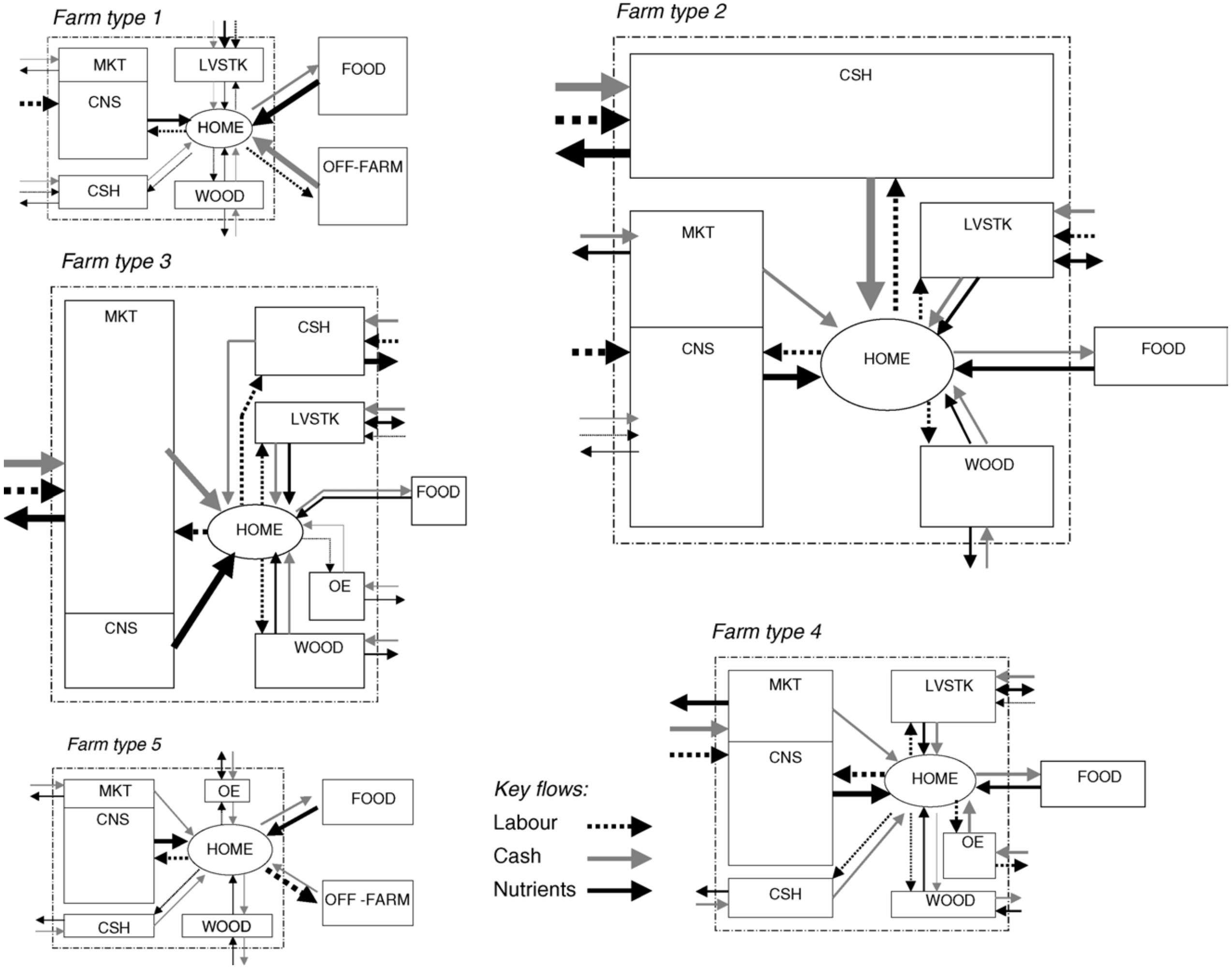

Fig. 2. Graphic models of farms of types 1–5. The size of the components as well as of the system boundaries indicate their relative size and/or importance in reality (e.g. the size delimited by the boundaries indicates land size). The weight of the arrows indicates the relative importance of the flows they symbolise. For the sake of simplicity not all possible flows are included. HOME: household (family size); CNS: food crops consumed by the household; MKT: surplus of food crop produce sold on the market; CSH: cash crops; LVSTK: livestock; WOOD: woodlot, mainly for fuel; FOOD: external source of food items (market); OFF-FARM: external source of income; OE: other enterprises, which comprise income-generating activities that involve on-farm production factors (e.g. honey bees, oxen-ploughing services, etc.).

Table 4
Average values of socio-economic indicators and land:labour ratios for the different farm types at the three sub-locations

Sub-location (S)	Farm type (FT)	Farm size (ha)	Cropped area (ha)	Family size	Family members working		Hired labour (m-d year^{-1})	Land available per labour unit[a]		Income from farming (%)	Self-sufficiency of maize (months)	Livestock[b] ownership (heads)
					On-farm	Off-farm		Family	Total			
Emuhaia	1	0.6	0.7	4.8	3.2	1.7	4.2	0.22	0.07	38	6.2	3.0
	2	2.1	2.1	7.1	3.3	1.2	7.0	0.63	0.20	50	11.0	4.0
	3	0.7	0.8	7.6	4.2	0.8	1.4	0.22	0.13	71	8.0	3.2
	4	0.3	0.3	5.7	4.0	0.3	0.7	0.10	0.07	73	5.7	2.7
	5	0.5	0.4	5.3	1.5	1.3	0.0	0.27	0.27	53	1.5	0.8
Shinyalu	1	0.6	0.6	5.0	2.7	0.9	5.0	0.30	0.08	50	8.7	1.7
	2	1.6	1.3	8.3	5.0	0.7	8.7	0.35	0.11	77	11.0	5.0
	3	1.3	1.3	8.0	4.2	0.6	4.4	0.43	0.15	80	9.6	2.8
	4	0.7	0.6	4.8	2.5	0.3	2.0	0.32	0.17	95	9.1	6.3
	5	1.0	0.8	5.5	2.8	1.0	0.5	0.42	0.35	73	6.3	0.3
Aludeka	1	1.4	1.1	5.7	3.7	1.0	6.7	0.39	0.12	58	5.7	2.7
	2	3.8	2.6	8.3	5.5	0.3	6.8	0.68	0.30	84	6.8	2.3
	3	1.8	2.2	8.4	3.6	0.4	4.8	0.68	0.24	78	8.4	4.0
	4	1.2	0.9	6.0	2.9	0.2	1.2	0.39	0.26	84	4.6	2.4
	5	1.2	1.0	6.3	3.3	0.7	0.0	0.40	0.40	53	3.3	1.7
S.E.D.	(S)	0.23	0.18	0.99	0.56	0.23	0.43	0.07	0.06	6.4	0.98	0.87
	(FT)	0.29	0.23	1.39	0.71	0.29	0.55	0.08	0.08	8.1	1.25	1.11
P-value	(S × ST)	0.384	0.236	0.992	0.600	0.759	0.063	0.329	0.292	0.785	0.697	0.052

S.E.D.: standard error of the differences; *P*-value: probability value from ANOVA table.
[a] Ratios were calculated considering only family members working on-farm (family), and including also hired-in labour (total).
[b] Including cattle, sheep, goats and pigs.

limitations. Certain enterprises (OE in Fig. 2) such as honey production were seen as alternative income-generating activities. Although type 4 was the most heterogeneous group, a common denominator was that livestock keeping appeared as one of the most relatively important farm activities in terms of labour allocation (Fig. 2 and Table 4). They had a variable source of off-farm income from temporary businesses (e.g. women bought maize grown in other areas and retailed it at the farm gate), leasing labour or oxen services. Farms of type 5 were land-constrained and one or more family members worked casually for other farmers. This intermittent, low-skilled source of employment generated low wages and created an important labour shortage within their own household. Most households headed by women (widows) were found within this farm type.

Across sub-locations, larger farms and the largest areas under crops were found in types 2 and 3, which often included different soil types along a catena (cf. Fig. 1); however, some farmers extended the area under crops by annexing/hiring land (Table 4). Although all farm types from 1 to 4 hired some labour during the season, types 1 and 2 were those that effectively covered their labour demands by hiring. The land:labour ratio calculated on the basis of family size and family labour (i.e. the number of family members living and effectively working on the farm) did not differ significantly between farm types except for Emuhaia, due to the smaller farm sizes. When hired labour was included in the calculation, type 5 farms appeared mostly labour-limited while type 1 farms were mainly land-limited. The land:labour ratios were not significantly different between the food-sufficient farm types 2 and 3, nor between types 3 and 4. Larger land:labour ratios were found in Aludeka, where land was left uncultivated during the growing season in most farms.

3.3. Soil fertility management and nutrient flows

The frequency of adoption of management practices such as fallow and crop rotation varied between sub-locations and farm types, and were

Table 5
Frequency of adoption of management practices affecting soil fertility amongst the farms visited, stratified according to the proposed typology for each sub-location

Sub-location	Farm type	*n*	% of farmers that practice		% of farmers that use	
			Fallow	Crop rotation	Compost	Fertilisers[a]
Emuhaia	1	5	20	20	100	100
	2	3	33	33	67	67
	3	5	40	60	100	100
	4	3	33	66	100	67
	5	4	25	0	75	0
Total/mean		20	30	35	90	70
Shinyalu	1	3	0	33	67	100
	2	3	67	67	67	100
	3	5	60	60	80	80
	4	4	25	0	75	100
	5	4	25	50	50	75
Total/mean[b]		19	37	42	68	90
Aludeka	1	3	33	100	33	33
	2	5	100	100	60	60
	3	5	80	100	40	20
	4	4	50	100	0	25
	5	3	33	100	0	0
Total/mean		20	65	100	35	25

[a] Mineral fertilisers available on the market (e.g. urea, TSP, etc.).
[b] Answers given in one of the farms were not reliable after triangulation.

normally constrained by land size due to the double-cropping system (Table 5). Although most farmers in Emuhaia and Shinyalu used fertilisers, the application rates were generally low, and important differences were observed between farm types (see later). Most frequently used organic fertilisers were cattle manure either applied pure or composted together with other organic resources such as crop residues. They were less frequently used in Aludeka due to a smaller cattle population, lack of experience with composting and a less efficient collection of manure (i.e. free grazing).

The total production of food crops estimated for the selected case-study farms, a rough indication of the main outflow of nutrients from the fields, varied consistently between farm types across sites (Table 6). Larger figures for Aludeka were the result of larger farm sizes, and the important contribution of cassava and sweet potato to total food production. The non self-sufficient farm types 1, 4 and 5 produced less than 2 t of food in all sub-locations, and food production per capita was always below 0.1 t for farms of type 5. Type 1 farms, with almost the same average land area than type 5, produced two to four times more food due to their capacity to intensify production in terms of inputs and labour. In all sub-locations, grain production by type 4 and type 5 farms was lower than the often-assumed annual requirement of 170 kg person^{-1} (Shepherd and Soule, 1998). For Emuhaia, Shinyalu and Aludeka, respectively, average grain yields were slightly above, equal to or just below 1 t ha^{-1}.

Due to the smaller farm sizes of Emuhaia, the application rates of mineral fertilisers were higher than for the other localities (Table 7). However, the largest fertiliser use intensity (total amount used over total cropped land) was found in Shinyalu. In Aludeka, fertiliser use was restricted only to the wealthiest farms. The main type of mineral fertiliser used in all sub-locations was diammonium phosphate (18:46:0) at planting, followed by calcium-ammonium nitrate and urea (46:0:0) for top dressing. Rock phosphate and triple super phosphate were less widely used. Tea growers used a compound fertiliser (25:5:15) obtained through the tea processing industry. A certain degree of substitution of organic resources by mineral fertilisers was observed for the largest and wealthier type 2 farms with ample labour for distribution of

Table 6
Food and grain production by 15 case-study farms representing all farm types at each sub-location

Sub-location	Farm type	Food production[a]			Grain production		
		Total per farm (t)	Per capita (t)	Sold to market (%)	Total per farm (t)	Average yield (t ha^{-1})	Share of total cropped area (%)
Emuhaia	1	0.9	0.2	9	0.2	1.3	33
	2	2.8	0.4	45	1.1	1.3	32
	3	5.9	0.6	56	4.8	2.5	53
	4	1.0	0.2	16	0.3	1.1	55
	5	0.6	0.1	14	0.2	0.6	41
Shinyalu	1	1.9	0.3	2	1.1	1.4	73
	2	3.6	0.4	43	1.5	1.2	43
	3	6.3	1.3	52	1.3	1.2	53
	4	1.9	0.5	29	0.6	0.7	73
	5	0.6	0.1	7	0.3	0.4	93
Aludeka	1	1.4	0.5	32	0.6	0.8	69
	2	4.9	0.6	31	1.3	1.0	41
	3	9.1	1.1	67	5.6	0.8	86
	4	1.4	0.3	22	0.3	0.4	48
	5	0.7	0.1	6	0.1	0.5	22

Estimations of resource flows from amounts indicated by farmers in local units during interviews on soil fertility management.
[a] Biomass of all edible crop parts (i.e. grains, tubers, stems and leaves, fruits, roots).

Table 7
Fertiliser use by 15 case-study farms representing all farm types at each sub-location, and average C, N, P and K application rates[a] as organic and mineral fertilisers

Sub-location	Farm type	Mineral fertilisers		Organic fertilisers		Average input rates (kg ha^{-1})			
		Use intensity (kg ha^{-1})	Average rate (kg ha^{-1})	Total use (t)	Use intensity (t ha^{-1})	Organic	Macronutrients		
						C	N	P	K
Emuhaia	1	48	92	2.2	8.0	4420	116	58	118
	2	16	66	0.9	0.5	510	27	25	14
	3	26	17	2.3	4.0	3150	72	34	84
	4	6	43	0.7	1.3	1830	44	25	49
	5	12	16	0.3	0.5	2770	58	24	44
Shinyalu	1	51	25	0.8	1.0	660	26	19	18
	2	32	82	0.2	0.1	140	26	18	4
	3	9	14	0.4	0.2	530	24	12	14
	4	22	18	0.2	0.2	320	14	10	9
	5	5	7	0	0	0	3	3	0
Aludeka	1	2	14	0	0	0	3	7	0
	2	6	33	0	0	0	1	2	0
	3	0	0	0	0	0	0	0	0
	4	0	0	0	0	0	0	0	0
	5	0	0	0	0	0	0	0	0

Estimations of resource flows from amounts indicated by farmers in local units during interviews on soil fertility management. Use intensity: total amount used (total use) divided by the total cropped area per farm; average rate: amount of fertiliser applied to a certain field divided by its area (dose), calculated for each individual field that received mineral fertilisers and averaged at farm scale; total use: total amount of fertiliser used per farm.
[a] The average at farm level considered only those fields where fertiliser inputs had been used.

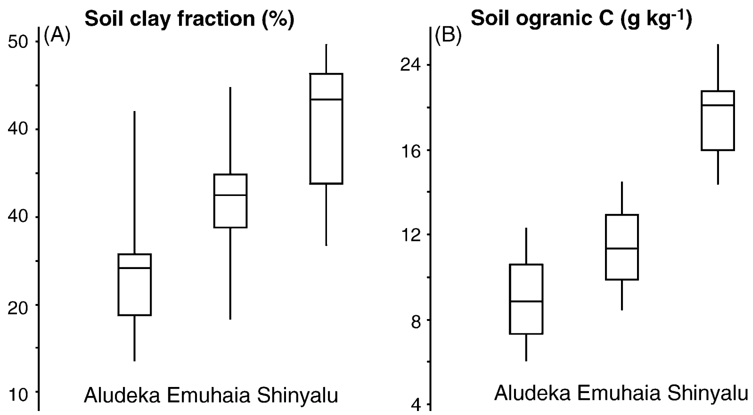

Fig. 3. Ranges of (A) clay content [%] and (B) soil organic carbon [g kg^{-1}] for the soil samples from Aludeka, Emuhaia and Shinyalu, western Kenya. The box-and-whisker diagrams include the range of 50% of the samples (rectangle), the median (cross bar) and the maximum and minimum values (extreme of the lines). Sample sizes: 53 (Aludeka), 55 (Emuhaia), 53 (Shinyalu).

manure across different fields. The C, N, P and K application rates (Table 7) indicated that type 1 farms were those concentrating most nutrients in their land, due to their smallest outputs to the market.

3.4. Soil fertility status

The strong difference in clay content in the soils from Aludeka to Shinyalu induced important differences in the fertility of the soils sampled from production units at each site (Fig. 3A). In Aludeka, many sampling points were on the sandy, flat soil-landscape units occupied by the locally known as *Assinge* soil. In Emuhaia, some production units were found on the sandy *Oluyekhe* soils in shallow valleys or surrounding rocky outcrops. In Shinyalu, production units on sandy valley bottomlands were less frequent since they are less accessible due to the steeper topography. Fields sampled at Shinyalu had a much higher C content in their topsoil than those at the

Table 8
Weighted average C and macronutrient content in the topsoil of the 15 case-study farms at the three sub-locations

Sub-location	Farm type	Weighted average content					
		Soil organic C (g kg^{-1})	Total soil N (g kg^{-1})	Extractable P (mg kg^{-1})	Exchangeable cations ($cmol_{(+)}$ kg^{-1})		
					K^+	Ca^{2+}	Mg^{2+}
Emuhaia	1	9.7	1.1	4.8	0.4	2.8	1.5
	2	12.0	0.8	6.4	0.4	4.2	1.3
	3	11.7	1.3	4.3	0.9	4.6	2.3
	4	13.6	1.3	2.8	0.2	4.2	1.3
	5	10.6	1.0	2.4	0.4	2.9	1.1
Shinyalu	1	17.5	1.5	4.5	0.2	4.2	1.4
	2	17.1	1.7	10.1	0.3	6.3	1.8
	3	18.7	1.5	2.5	0.5	7.1	2.5
	4	16.3	1.6	1.8	0.2	6.6	3.6
	5	17.4	1.6	2.1	0.5	7.9	2.2
Aludeka	1	10.8	0.6	4.6	0.3	3.8	1.1
	2	9.1	0.6	5.0	0.2	3.8	0.8
	3	9.6	0.7	4.0	0.7	2.9	1.1
	4	6.2	0.4	4.2	0.2	2.7	0.6
	5	4.8	0.2	2.2	0.2	0.9	0.2

other sub-locations (Fig. 3 B), in line with the trend observed for clay content. Differences in clay and C contents were also reflected by the trends of the effective cation exchange capacity (ECEC) and the sum of exchangeable bases (Ca + Mg + K + Na) across localities (Table 8). The pH_{water} (1:2.5) measurements (data not shown) also revealed that the topsoil of the fields sampled in Emuhaia and Shinyalu tended to be more acid than those of Aludeka.

Although larger farms tended to include inherently more variability (i.e. soil/landscape units, cf. Fig. 1), soil properties for organic C and most nutrients in all sub-locations did not indicate clear differences between farm types (Table 8). The strongest differences between farm types were observed for extractable P. For the exchangeable bases, the inherent soil properties play also a role in explaining, e.g. the somewhat similar values observed in the case study-farms types 3 and 5 of Shinyalu, which shared the same soil-landscape unit in the field (i.e. next-door neighbours).

4. Discussion

Important differences in terms of socio-economic and biophysical aspects that may affect soil fertility management were found between the three localities selected for the study (cf. Table 1 and Fig. 1). The biophysical and socio-economic conditions of Aludeka (Teso district) contrasted strongly with those of Emuhaia (Vihiga district) and Shinyalu (Kakamega district), which in turn were ethnically and agroecologically closer, and differed mainly in population density and accessibility to urban centres and markets. Different production situations and orientations (i.e. low or high input use, market-oriented or self-subsistence) were the consequence of the interaction between factors operating at region and sub-location scales (i.e. between- and within-sub-location variability) (cf. Table 4). Aludeka, in particular, was an interesting sub-location due to its low population density, high soil variability and relative isolation from factor markets. However, its inclusion generated a certain degree of distortion in the characterisation of the farming systems due to the low cattle population, strongly affected by a perennial *Tse-Tse* fly problem in the area.

To investigate relationships between soil fertility and management at farm scale, a classification or typology of farms was necessary. Gender and educational level of the household heads, classical wealth indicators such as farm size, type of homestead, livestock ownership or self-sufficiency of food and fuel, labour availability and access to off-farm income, food habits, and input use intensity varied widely between sub-locations (cf. Tables 1, 4, 5, 6 and 7). As in previous studies carried out in western Kenya (e.g. Soule and Shepherd, 2000), farm stratification following a purely ‘wealth-approach’ led to poor differentiation of households. Clearly distinct patterns of nutrient flows and transfers were often found only for farms of high resource endowment, in contrast with those of medium to low resource endowment. However, such farms may represent only 10% of all farms in a certain location. Evidently, further stratification criteria were required to allow greater discrimination of moderate and poor endowment classes for a typology and to reveal the ‘hidden’ variability between farming households. Distinctions have been made between structural typologies, (i.e. production factors and how they are managed), and functional typologies (i.e. decision-making by farmers given the constraints and their behaviour in the face of climatic fluctuations or changing socio-economic situations) (Mettrick, 1993). A combination of both seemed most adequate in this case.

Information on relative factor (labour, capital) scarcity was also used, as determined by household-specific variables such as market information and access to factor markets (Kuyvenhoven et al., 1995). The importance of agriculture and production goals varied strongly within wealth classes (Fig. 2). Among the rich were both farmers who relied mainly on off-farm earnings or remittances and farmed relatively small pieces of land for self-consumption (type 1) and those who farmed large areas mainly with cash crops for the market (type 2). The poorest farmers (type 5) also farmed small pieces of land and derived a large proportion of their income off-farm, similar to type 1 farmers (Fig. 2, Table 4). However, in this case the type 5 farmers (often widows, or single-headed households) sold their labour locally (in stark contrast with type 1 farms), which resulted in severe labour shortages on their own farms. Farms of types 3 and 4 were intermediate representing diverse strategies

revolving around production of crops for self-consumption and the market, including producing fodder (Napier grass) for sale to wealthier livestock owners.

Thus, the typology of farms gave insight into how wealth is generated and re-invested, affecting resource flows within and between farms and allowing discrimination between farm types that were land- or labour-limited, or both. When the land:labour ratios were calculated for the different farm types, considering also hired labour, type 1 farms were seen clearly land-limited and type 5 farms appeared labour-limited (cf. Table 4). These represent constraints to soil fertility management, affecting e.g. the practice of fallow (which requires land) or fertiliser use, which is both demanding of cash and labour-intensive and was shown as positively influenced by (domestic or external) labour availability in Kenya (Omamo et al., 2002). Considering the age of the household head and the family structure was used to include the concept of the 'farm developmental cycle' (Crowley et al., 1996) in the farm categorisation. The attitudes towards risk (investments) and innovation are highly variable according to the phase of the farm developmental cycle in which the household is (land, capital and/or labour constraints are also related to this).

As in previous studies (e.g. De Jager et al., 2001), access to off-farm income was a major variable affecting livelihoods and farm management across and within sub-locations. Alternative sources of income varied widely in terms of labour/return ratios, and depended on degree of education as well as on access to labour markets (i.e. proximity to urban areas). Off-farm income has a variety of effects on soil fertility. Cash flows generated allow a higher rate of input use but may cause a shortage of labour within the farm that, according to the magnitude of these cash flows, may be compensated by hiring casual labour (cf. Table 4). Hiring labour was common in the more populated areas (Emuhaia) while hiring land was often seen in the less populated areas (Aludeka). Concomitantly, a trend towards production intensification was observed in Emuhaia, contrasting with the extensive production system relying on crop rotation and fallow practices in Aludeka. The extent of use of nutrient inputs, both mineral fertilisers and organic residues, also varied strongly between sub-locations with fewer inputs used in Aludeka where land sizes were larger, the population less dense and markets more remote (Tables 5 and 7).

The differences in soil fertility between sub-locations could be largely explained by inherent soil properties, derived from the characteristics of the parent materials and the interaction of the soil forming factors (Fig. 3A and B). In spite of other factors controlling soil organic C (i.e. climate, vegetation and long-term management) texture explained to a large extent the variation observed between sub-locations due to the greater capacity for physicochemical C stabilisation in soils richer in clay and silt (Feller and Beare, 1997; Hassink, 1997). Similarly, the variations in ECEC and soil pH might be partly due to inherent differences in soil type and climate: highly weathered, low-saturated red soils developed under forest vegetation in Shinyalu and Emuhaia compared with brown and reddish soils developed from mineral-carrying fluvial sediments in Aludeka (Braun et al., 1997). This was also reflected in differences in extractable P: the lowest concentrations, in absolute terms, were measured in individual samples from the more depleted, P-fixing soils of Emuhaia. However, the differences observed for extractable P could not be explained by considering only the inherent soil properties and must be partly controlled by management factors. Indeed, differences in wealth between farms were reflected mostly by input use intensity, particularly on mineral (P) fertiliser use (cf. Table 7), and the strongest differences in soil fertility status between farms belonging to the various farm types in each sub-location were observed for extractable P (cf. Table 8). Vanlauwe et al. (2002) also observed that the soil available P status was more favourable in Southern Benin Republic compared to Northern Nigeria and pointed at the frequent use of P-containing cotton fertilizer in Southern Benin as one of the potential factors explaining this. Exactly the opposite was found for Emuhaia, where farms have an average size of less than one hectare, with soil exhaustion caused by continuous farming with few or no nutrient inputs. The effect of wealth and production orientation could be seen in the magnitude of the nutrient inputs and outputs to and from the farm, in farm size (and associated spatial variability – cf. soil catenas in Fig. 1) and in labour availability. However, these differences were in general not reflected by the overall soil fertility status at farm scale, except for P (cf.

Table 8). Further explanations to this site-specific variability should be sought at more detailed scales of analysis, considering the heterogeneity in nutrient balances and stocks within the farms, and its interaction with factors determining decisions on resource allocation.

5. Conclusions

The selected sub-locations, Emuhaia in Vihiga district, Shinyalu in Kakamega district and Aludeka in Teso district, were representative of the variation in biophysical and socio-economic conditions found in western Kenya. Most trends and figures on socio-economic and managerial aspects available in different sources were confirmed by those extracted from the samples of farms selected at each sub-location in this study. Adding household objectives and socio-economic constraints to the sole resource endowment criterion improved farm categorisation, when management decisions, resource allocation patterns and nutrient flows are to be assessed. The different strategies for income generation and the variable factor constraints faced by each of these farm household types affect decisions on land use and general management practices, which impact on soil fertility management. Farms of small size (types 1, 4 and 5) and therefore not self-sufficient in food production, had clearly different labour allocation strategies: to rely on off-farm earnings (salary, pension, remmitances) and businesses, to prioritise livestock keeping relative to other activities (milk, oxen services), or to lease labour force to wealthier farmers in change of food and low wages. Each of these strategies had a different impact on soil fertility management within those farms, as they affect their capacity to buy fertilisers or other inputs, their availability of organic resources, and their land:labour ratios.

Important differences in soil fertility in western Kenya can be explained by the inherent properties of the soils – related to their catenary position – and particularly clay content. The intensity of resource use increases in areas of high population density, closer to urban centres, and where soil fertility depletion is widely recognised by farmers. Land and labour constraints to agricultural production, which often affect soil fertility management, can be partially removed by hiring them in, according to their relative scarcity at each particular sub-location. Differences in household wealth and production orientation are mainly reflected in the pattern of resource flow at farm scale; although the magnitude of nutrient flows to and from the farm vary for the different farm types, no clear differences in nutrient stocks and availability were found at farm scale except for available P. To further understand differences in soil fertility status as affected by the various biophysical and socio-economic factors identified here, analyses must be performed at a more detailed scale of analysis, i.e. at the field level within a single farm.

Acknowledgements

We acknowledge Bundesministerium für Wirtschaftliche Zusammenarbeit und Entwicklung (BMZ) for providing the necessary financial support in the framework of the project on 'Improving Integrated Nutrient Management practices on small-scale farms in Africa'. We also thank John Mukalama and Isaac Ekise (TSBF) and Walter Munyuere (Kenya Rural Extension Service) for their skilled assistance, and Dr. Stephen Nandwa (National Agricultural Research Laboratory), Dr. Joshua Ramisch (TSBF-CIAT) and Mr. Daniel Rotich (Kenya Agricultural Research Institute) for sharing their experience.

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